Analyses of tagging data for evidence of decreased fishing mortality for large Gulf of Maine Cod, *Gadus morhua*

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Introduction

Using the age-structured production model (ASPM), Butterworth and Rademeyer (2008b) determined that an assumption of a dome-shaped selectivity pattern for instantaneous fishing mortality fit Gulf of Maine Cod data better than a flat-topped selectivity pattern. The hypothesis of a strong dome-shaped selectivity pattern on all gear can be difficult to evaluate since relatively low catches of older fish could be explained either by a dome-shaped selectivity or by actual low abundance of older animals caused by high mortality. Tagging data gives an opportunity to distinguish between these hypothesis, since the actual population of tagged fish at release are known.

Here we perform two complimentary analyses of Atlantic cod tagging data from a tagging study carried out by the Gulf of Maine Research Institute (Tallack 2007) using the methodology we employed previously for yellowtail flounder (Miller et al. 2008). The first compares expected probability of recovery by age class for tagged fish based on estimates of age-specific fishing mortality by Butterworth and Rademeyer (2008a) and a standard VPA with the observed proportions of recoveries for different length classes (and approximate corresponding ages) in the Atlantic cod tagging data. The second analysis fits a finite-state continuous-time model (Miller and Andersen 2008; Miller et al. 2008; Miller and Tallack 2007) to the Atlantic cod tagging data to estimate different fishing mortality parameters within the Gulf of Maine, Georges Bank and Canadian 4X stock areas for fish in three size classes (≤ 60, > 60 and ≤ 85, > 85) at release. Maximum likelihood estimates of instantaneous migration, natural mortality and tag-shedding rates, tag reporting probability and a non-mixing scalar to adjust fishing mortality in the first month after release are also provided by the second analysis. Although the latter parameters are not the focus here, it is desirable to "control" for different migration between and mortality rates within regions when estimating these size-specific fishing mortality rates.

A simple model for estimating the probability of recapture of a tagged fish

Let F_a, M_a and $Z_a = F_a + M_a$ denote fishing, natural, and total mortality at age a, respectively. Suppose a fish was tagged at age A. Its probability of recapture is:

$$R_A = \frac{F_A}{Z_A}[1 - \exp(-Z_A)] + \sum_{a=A+1}^{\infty} \frac{F_a}{Z_a}[1 - \exp(-Z_a)] \exp(-\sum_{\alpha=A}^{a-1} Z_\alpha) \tag{1}$$

This equation assumes no tagging induced mortality. Additionally, actual tagging recovery rates may be reduced because some tags are not reported. Both these factors would cause the proportion of tags that are reported recaptured to be less than that calculated in equation (1); if both these factors are independent of age, they would simply reduce R_A by a constant for all ages. If the tagging experiment began n years ago, only recoveries at time less than n will be recorded. In such a case, the infinite series in equation (1) would be truncated:

$$R_A(n) = \frac{F_A}{Z_A}[1 - \exp(-Z_A)] + \sum_{a=A+1}^{n-1} \frac{F_a}{Z_a}[1 - \exp(-Z_a)] \exp(-\sum_{\alpha=A}^{a-1} Z_\alpha) \tag{2}$$

Since the tagging began in 2003, we used $n = 4$ years in the above equation.

If natural mortalities are constant with age, but fishing mortalities decrease with age because of dome-shaped selectivity, equations (1) or (2) predict that fraction of fish that are recovered will decline as the age of tagging A increases. We illustrate this using the fishing mortalities and dome-shaped selectivity estimated by Butterworth and Rademeyer (2008b) in their base case, and compare these to the predictions from selectivity estimates from a VPA analysis of Gulf of Maine cod (Mayo per. comm.). The Butterworth and Rademeyer (2008b) base case estimated fishing mortality to peak at 0.26 at age five, and then declines severely for older ages (Table 1). By contrast, the VPA estimates that the fishing mortality at age 5 is only slightly greater than that for older ages (Table 1). Both of these mortality estimates imply an increasing probability of recapture between ages 1 and 4 (corresponding to lengths 30-67 cm; Figures 1-2). The fishing mortalities estimated in Butterworth and Rademeyer (2008b) imply a decreasing probability of recapture from age four onward, whereas the VPA predicts recovery rates to be essentially constant from age four.

These predictions can be compared to recoveries at length for a large scale Atlantic cod (over 113,000 releases, with over 6000 reported recaptures) tagging experiment conducted in the Gulf of Maine, Georges Bank and Canada (Figure 3). Tagging recovery rates combined over all regions showed an increasing rate of recovery for lengths between 35 and 70 cm, consistent with model predictions. Recovery rates between 70 and 115 cm do not indicate the declining trend with length that would occur with strongly domed selectivity. Regional recovery rates can also be determined for Gulf of Maine and Georges Bank cod. For Gulf of Maine cod, there is little evidence of any trend with length, except possibly at the smallest (35-45 cm) length bins. By contrast, a clear increasing trend with length from 35 to 70 cm is evidence from the Georges Bank cod tagging data, with a roughly flat selectivity afterwards. One possible cause of these differences is that there were many more releases on Georges Bank (79897 vs. 25449 in the Gulf of Maine) and about 85% of these were less than 70 cm in length, compared to 45% in the Gulf of Maine.

A finite-state continuous-time model for Atlantic cod tagging data

The Gulf of Maine Research Institute (GMRI) released over 100,000 conventionally tagged Atlantic cod in the Gulf of Maine, Georges Bank and Canadian 4X regions between 2003 and 2005. Some fish were released with either high or low-reward tags and some were released with 2 tags. Over 6000 individuals have been recovered to date, but we will consider the end of 2006 as the end-time of the study to reduce problems relating to delay of reporting recovered tags. We use the statistical modeling framework developed by Miller and Andersen (2008) with the times and regions of release and recovery, the type of tag (high-reward or low-reward) and the number of tags for each tagged fish as data. The regions of interest are the Gulf of Maine, Georges Bank and the Canadian 4X area.

States of the FSCT process

When the kth tagged fish is released in one of three regions at time $t_{0,k}$ it may at any instant move to one of the other two regions or die due to fishing or natural causes (given fishing activities are occurring) or it may shed the tag and thereby remove itself from the study. If it is dies due to fishing at time $t_{r,k}$ in one of the three regions, it may be reported with probability $\rho < 1$ when the tag is the low-reward type. The low-reward tagged fish recovered may not be reported with probability $1-\rho$ and we assume that all high-reward tagged fish are reported. If the fish is released with two tags, each tag may at any instant shed as when there is a single tag, but one tag will still remain so that the fish remains in the study. The fish may also remain alive at the time of analysis t_a with 0, 1, or 2 tags, depending on how many it had at release. As such, there are 27 states that a double-tagged fish may exhibit and 18 states that a single-tagged fish may exhibit (Table 2).

The 27×27 instantaneous rate matrix is

$$\mathbf{A} = \begin{pmatrix} \boldsymbol{\mu}_2 & 2\lambda\mathbf{I} & \mathbf{0} & \rho\mathbf{F} & \mathbf{0} & (1-\rho)\mathbf{F} & \mathbf{0} & \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\mu}_1 & \lambda\mathbf{I} & \mathbf{0} & \rho\mathbf{F} & \mathbf{0} & (1-\rho)\mathbf{F} & \mathbf{0} & \mathbf{M} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}$$

where $\mathbf{I}$ is a 3×3 identity matrix and $\mathbf{0}$ is a 3×3 matrix of zeros in the first two rows and a 21×3 matrix of zeros, otherwise. The elements, $\mathbf{F}$ and $\mathbf{M}$ are 3×3 diagonal matrices of regional instantaneous fishing $((F_{GOM}, F_{GB}, F_{4X})^T)$ and natural mortality rates $((M_{GOM}, M_{GB}, M_{4X})^T)$, respectively, λ is the instantaneous tag-shedding rate and ρ is the reporting probability for low-reward tags. For individuals released with low-reward tags, $0 < \rho < 1$ and we assume $\rho = 1$ for high-reward tags. The remaining elements contain the instantaneous migration rates and forces of transition from the states along the diagonal,

$$\boldsymbol{\mu}_2 = \begin{pmatrix} -a_1 & \mu_{GOM>GB} & \mu_{GOM>4X} \\ \mu_{GB>GOM} & -a_2 & \mu_{GB>4X} \\ \mu_{4X>GOM} & \mu_{4X>GB} & -a_3 \end{pmatrix}$$

and

$$\boldsymbol{\mu}_1 = \begin{pmatrix} -a_4 & \mu_{GOM>GB} & \mu_{GOM>4X} \\ \mu_{GB>GOM} & -a_5 & \mu_{GB>4X} \\ \mu_{4X>GOM} & \mu_{4X>GB} & -a_6 \end{pmatrix}$$

where a_h is the sum of the elements of $\mathbf{A}$ in row h off the diagonal. The doubling of tag-shedding rates for double-tagged fish implies that the shedding processes of each tag are independent and that the corresponding rates are equal (cf. Xiao 1996).

To allow for different fishing mortalities of tagged fish k between the time of release $t_{0,k}$ and 1 month later $(t_{0,k} + 1/12)$ we allow a modification to the fishing mortality matrices in $\mathbf{A}$. The instantaneous rate matrix for this period is

$$\mathbf{A}^* = \begin{pmatrix} \boldsymbol{\mu}_2 & 2\lambda\mathbf{I} & \mathbf{0} & \rho\gamma\mathbf{F} & \mathbf{0} & (1-\rho)\gamma\mathbf{F} & \mathbf{0} & \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\mu}_1 & \lambda\mathbf{I} & \mathbf{0} & \rho\gamma\mathbf{F} & \mathbf{0} & (1-\rho)\gamma\mathbf{F} & \mathbf{0} & \mathbf{M} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}$$

where γ is a scalar to modify fishing mortality for the recent releases due to incomplete mixing. Note that this allows fishing mortality for the first month to be either less than that of other fish $(0 < \gamma < 1)$ or greater than that of other fish $(\gamma > 1)$.

Model and likelihood

We consider a single model that allows us to focus on differences in fishing mortality among size classes of Atlantic cod in the Gulf of Maine while accounting for movement between the three regions and different fishing mortality in the three regions. Specifically, we allow size-specific movement rates between regions, size- and region-specific fishing mortality rates and size-specific natural mortality rates as well as constant tag-shedding rate and reporting probability.

Let $Y_k(t) \in S = \{1, \ldots, h, \ldots, 27\}$ be the state tagged fish k is in at time $t_{0,k} \leq t \leq t_a$. Given a vector of unknown instantaneous rate parameters $\mathbf{a}$ in the instantaneous rate matrices, the likelihood we maximize is

$$\begin{aligned}\mathcal{L}(\mathbf{a}) = & \left\{ P_{Y_k(t_{0,k}),Y_k(t_{r,k}-)} a_{Y_k(t_{r,k}-),Y_k(t_{r,k})} \right\}^{I(Y_k(t_a)\in\mathcal{F})} \\ & \times \left\{ \sum_{Y_k(t_{a,k})\notin\{\mathcal{F}\}}^{H} P_{Y_k(t_{0,k}),Y_k(t_a)} \right\}^{I(Y_k(t_a)\notin\{\mathcal{F}\})} \end{aligned} \tag{3}$$

where $I(Y_k(t_a) \in \mathcal{F})$ is an indicator of whether the animal is in a caught and reported state at time of analysis and $I(Y_k(t_a) \notin \{\mathcal{F}\})$ is an indicator of whether the animal is in any other state at time of analysis (Miller and Andersen 2008, eq. 5). The first line in eq. 3 is the product of the probability of being alive in region of recovery just prior to capture at time $t_{r,k}-$ given $Y_k(t_{0,k})$ and the instantaneous rate of capture in the region where recovery occurred. The probability $P_{Y_k(t_{0,k}),Y_k(t_{r,k}-)}$ is the $(Y_k(t_{0,k}), Y_k(t_{r,k}-))$ element of the probability transition matrix, $\mathbf{P}(t_{0,k}, t_{r,k}-)$ and $a_{Y_k(t_{r,k}-),Y_k(t_{a,k})}$ is the $(Y_k(t_{r,k}-), Y_k(t_{a,k}))$ element of the instantaneous rate matrix ($\mathbf{A}$) appropriate to the interval that contains $t_{r,k}$. The second line in eq. 3 is the probability of being in any of the states not corresponding to capture and reporting at the time of analysis given $Y_k(t_{0,k})$ which is the sum of the elements of the probability transition matrix $\mathbf{P}(t_{0,k}, t_{a,k})$ in row $Y_k(t_{0,k})$ where $Y_k(t_{a,k}) \notin \{\mathcal{F}\}$. See Miller and Andersen (2008) for how the probability transition matrix is formed from the instantaneous rate matrix.

Results

The main finding here is the lack of a statistically significant difference between fishing mortality rates in the Gulf of Maine on Atlantic cod that had lengths at release in the middle and large length classes (Table 3). However, the natural mortality rate estimates are perhaps unrealistically high as was also found for Atlantic cod by (Miller and Tallack 2007).

Discussion

Neither of the analyses we undertook showed evidence (statistical or otherwise) that larger (older) Atlantic cod are subjected to lower fishing mortality in the Gulf of Maine than smaller (younger) Atlantic cod. Ideally, we would like to consider a model for the tagging data that allows fishing mortality to change over the life history of a given fish as it grows larger and older, because fish that are small at release will experience different fishing intensities as it grows. However, the use of size at release should provide results that are a good approximation.

It has been suggested by Butterworth and Rademeyer (2008b) that if only a portion of the older fish can be captured by surveys or fishing gear due, for example, to emigration, then a domed selectivity is compatible with a flat recapture rate for larger sizes. Such an assumption implies a non-homogeneous non-mixed population, contrary to not only the assumptions of the above models, but also to most stock assessment models including Butterworth and Rademeyer (2008b). If such strong non-homogeneity existed (though there is little evidence that it does), then the conclusions of both the above analyses and Butterworth and Rademeyer (2008b) would be invalid, including the likelihood calculations in the latter that indicate a greater likelihood for domed selectivity.

References

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Table 1. Estimated mortalities and tagged recovery probabilities based on the estimated selectivity and fishing mortalities from the standard VPA run and the base case of Butterworth and Rademeyer (2008b).

Age	Mean Length	VPA F_A	BR F_A	VPA $R_A(4)$	BR $R_A(4)$
1	30	0	0	0.15	0.18
2	56	0	0.01	0.29	0.29
3	61	0.02	0.13	0.42	0.40
4	67	0.32	0.25	0.56	0.43
5	71	0.37	0.26	0.57	0.38
6	79	0.34	0.22	0.56	0.30
7	93 (7+)	0.34	0.12	0.56	0.19
8	N/A	0.34	0.08	0.56	0.14
9	N/A	0.34	0.06	0.56	0.10
10	N/A	0.34	0.04	0.56	0.07

Table 2. States a tagged Atlantic cod may exhibit during the time of the study.

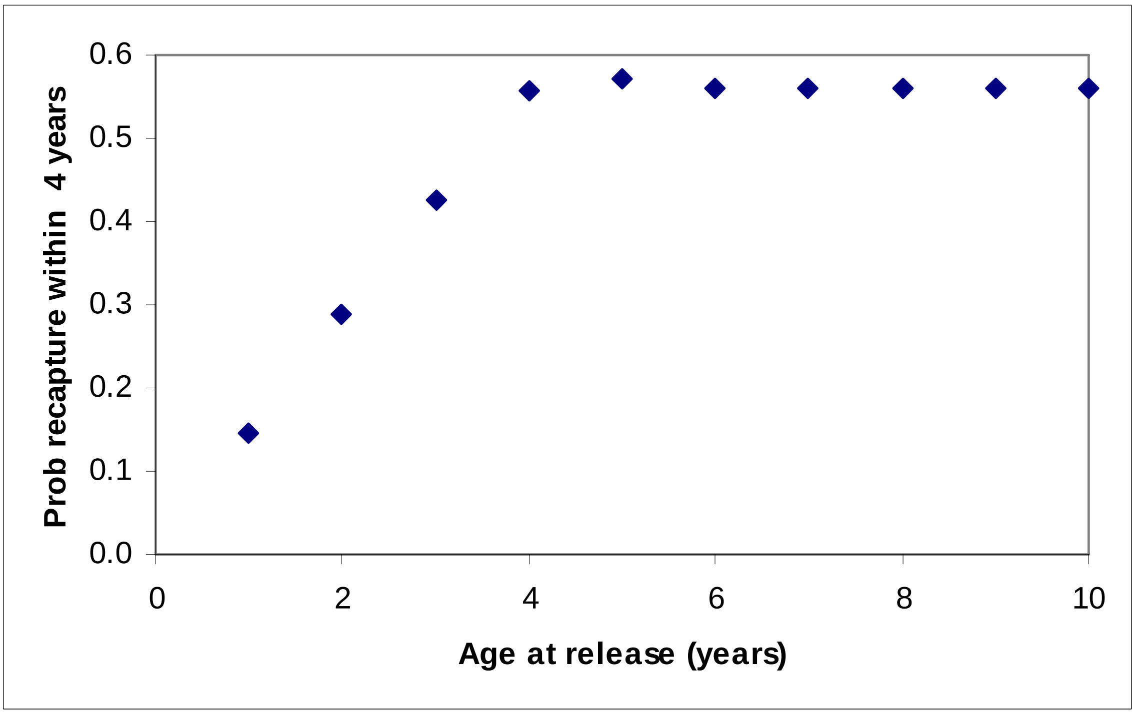
State	Definition
1	Alive in the Gulf of Maine with 2 tags
2	Alive in the Georges Bank with 2 tags
3	Alive in the CAN4X with 2 tags
4	Alive in the Gulf of Maine with 1 tag
5	Alive in the Georges Bank with 1 tag
6	Alive in the CAN4X with 1 tag
7	Alive in the Gulf of Maine with 0 tags
8	Alive in the Georges Bank with 0 tags
9	Alive in the CAN4X with 0 tags
10	Caught in in the Gulf of Maine with 2 tags and reported
11	Caught in in the Georges Bank with 2 tags and reported
12	Caught in in the CAN4X with 2 tags and reported
13	Caught in in the Gulf of Maine with 1 tag and reported
14	Caught in in the Georges Bank with 1 tag and reported
15	Caught in in the CAN4X with 1 tag and reported
16	Caught in the Gulf of Maine with 2 tags and not reported
17	Caught in the Georges Bank with 2 tags and not reported
18	Caught in the CAN4X with 2 tags and not reported
19	Caught in the Gulf of Maine with 1 tag and not reported
20	Caught in the Georges Bank with 1 tag and not reported
21	Caught in the CAN4X with 1 tag and not reported
22	Dead from non-fishing causes in the Gulf of Maine with 2 tags
23	Dead from non-fishing causes in the Georges Bank with 2 tags
24	Dead from non-fishing causes in the CAN4X with 2 tags
25	Dead from non-fishing causes in the Gulf of Maine with 1 tag
26	Dead from non-fishing causes in the Georges Bank with 1 tag
27	Dead from non-fishing causes in the CAN4X with 1 tag

Table 3. Parameter estimates and approximate 95% confidence intervals provided by the finite-state continuous-time model to Atlantic cod tagging data.

Parameter	$\widehat{\theta}$	CI_L	CI_U
$\mu_{L\leq 60,GOM>GB}$	0.04762	0.03374	0.06721
$\mu_{L\leq 60,GOM>4X}$	0.005277	0.003151	0.008838
$\mu_{L\leq 60,GB>GOM}$	0.1004	0.09335	0.108
$\mu_{L\leq 60,GB>4X}$	0.007781	0.006618	0.009149
$\mu_{L\leq 60,4X>GOM}$	0.06287	0.04069	0.09715
$\mu_{L\leq 60,4X>GB}$	0.4855	0.4192	0.5622
$\mu_{60>L\leq 85,GOM>GB}$	0.1338	0.1151	0.1556
$\mu_{60>L\leq 85,GOM>4X}$	0.02807	0.02246	0.03507
$\mu_{60>L\leq 85,GB>GOM}$	0.09265	0.08228	0.1043
$\mu_{60>L\leq 85,GB>4X}$	0.116	0.1055	0.1274
$\mu_{60>L\leq 85,4X>GOM}$	0.1014	0.07829	0.1313
$\mu_{60>L\leq 85,4X>GB}$	0.2194	0.1763	0.273
$\mu_{L>85,GOM>GB}$	0.176	0.1223	0.2533
$\mu_{L>85,GOM>4X}$	0.0484	0.02809	0.08337
$\mu_{L>85,GB>GOM}$	0.473	0.298	0.7508
$\mu_{L>85,GB>4X}$	0.4975	0.2797	0.8847
$\mu_{L>85,4X>GOM}$	5.607e-05	1.731e-25	1.817e+16
$\mu_{L>85,4X>GB}$	0.5987	0.2989	1.2
$F_{L\leq 60,GOM}$	0.09336	0.08636	0.1009
$F_{L\leq 60,GB}$	0.04472	0.04181	0.04784
$F_{L\leq 60,4X}$	0.259	0.2367	0.2834
$F_{60>L\leq 85,GOM}$	0.1822	0.17	0.1952
$F_{60>L\leq 85,GB}$	0.1165	0.1088	0.1248
$F_{60>L\leq 85,4X}$	0.3403	0.3127	0.3703
$F_{L>85,GOM}$	0.1894	0.1718	0.2089
$F_{L>85,GB}$	0.1417	0.1059	0.1897
$F_{L>85,4X}$	0.1639	0.122	0.2202
$M_{L\leq 60}$	0.4873	0.4623	0.5137
$M_{60>L\leq 85}$	0.9804	0.9488	1.013
$M_{L>85}$	1.011	0.9288	1.101
λ	0.1494	0.139	0.1606
γ	2.001	1.926	2.079
ρ	0.5395	0.5075	0.5712

Figure 1. Predicted probability of recapture within four years assuming fishing mortalities from the VPA (see Table 1) and natural mortality of 0.2, as a function of age (a) and length (b).

(a)



(b)

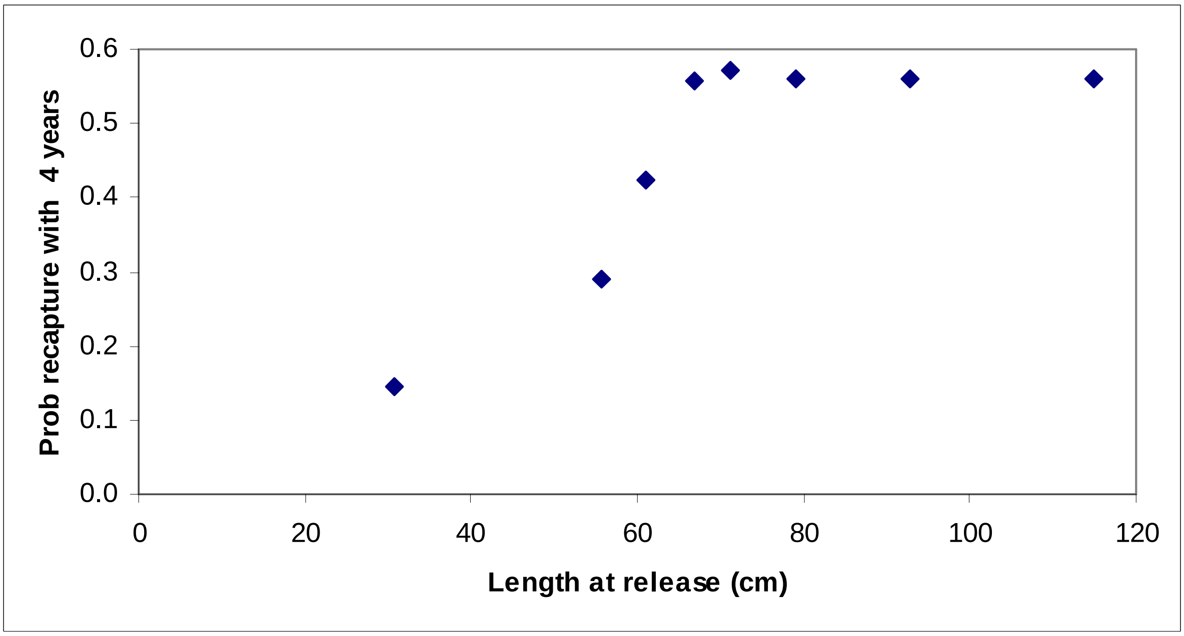
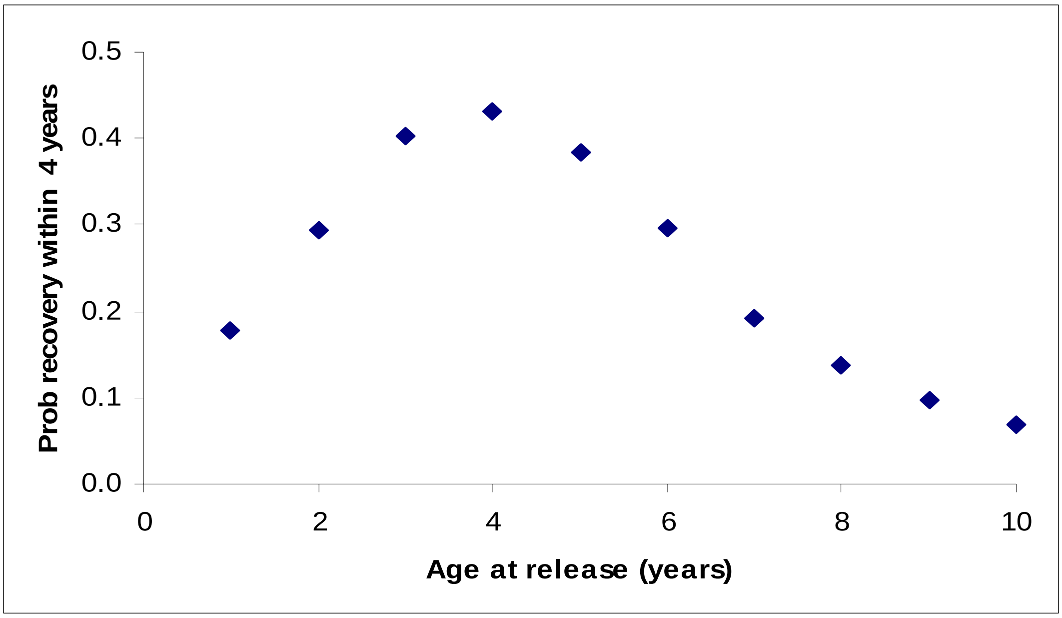


Figure 2. Predicted probability of recapture within four years assuming fishing mortalities from Butterworth and Rademeyer (2008) (see Table 1) and natural mortality of 0.2, as a function of age (a) and length (b).

(a)



(b)

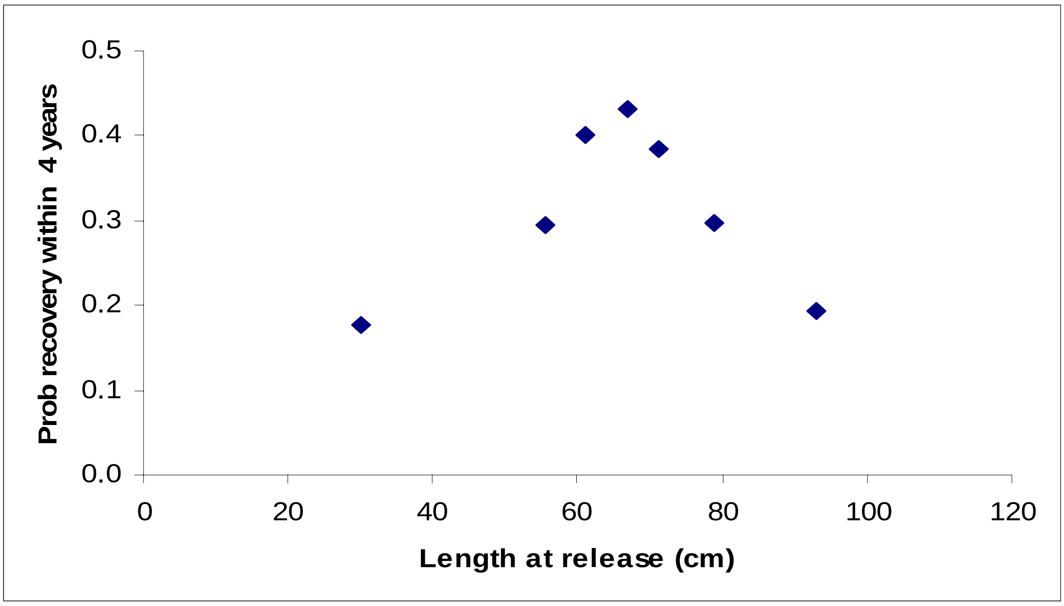
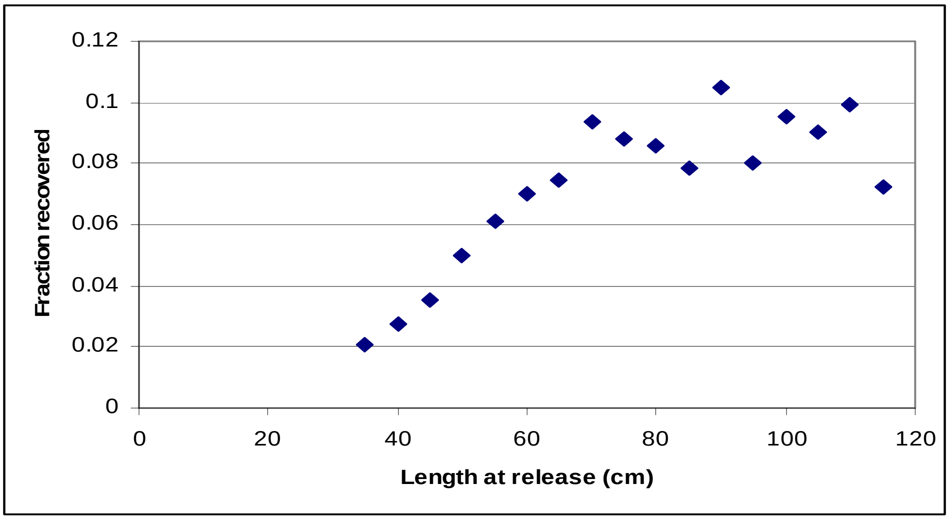
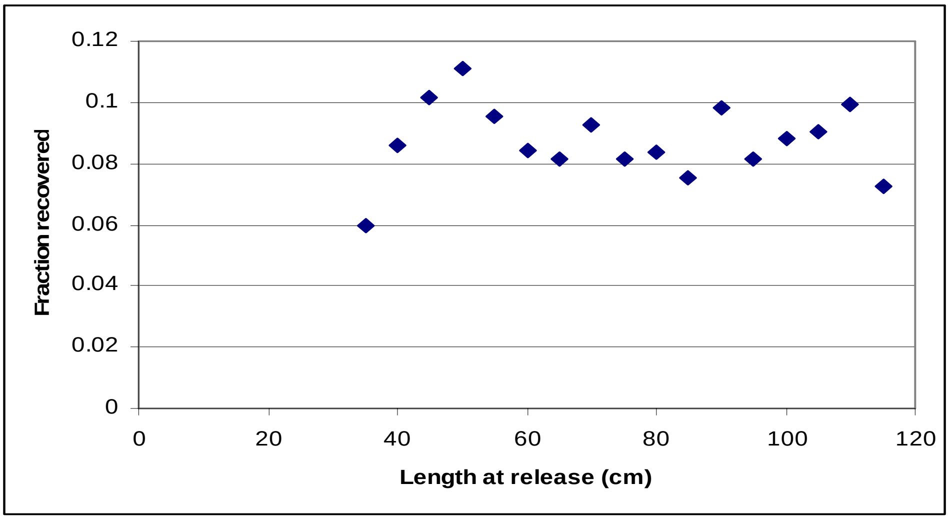


Figure 3. Recapture rates from the cod tagging experiment overall (a), in the Gulf of Maine (b), and on Georges Bank (c). The 115 cm length groups in (a) and (b), and the 100 cm group in (c) are plus groups.

(a)



(b)



(c)